EUSAR 2012

First Results from an Airborne Ka-band SAR using SweepSAR and Digital Beamforming

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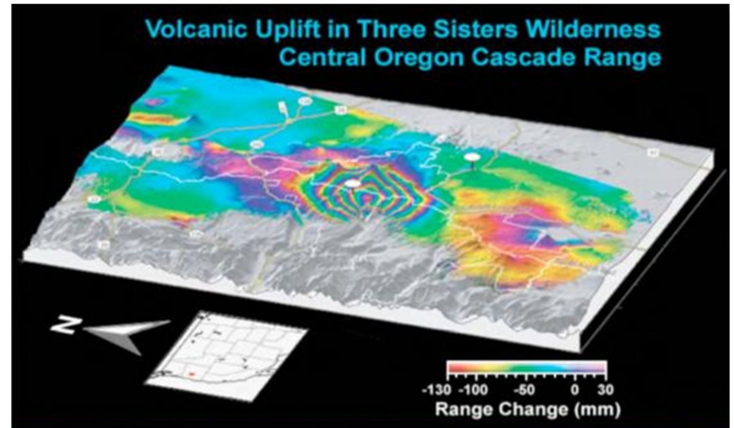
Outline

- SweepSAR Introduction
- SweepSAR Airborne Demonstration Description
  – Antenna System
  – Digital Beamforming System
- Airborne Experiment
- Calibration and Beamforming Techniques
- Results and Images
- Future Plans

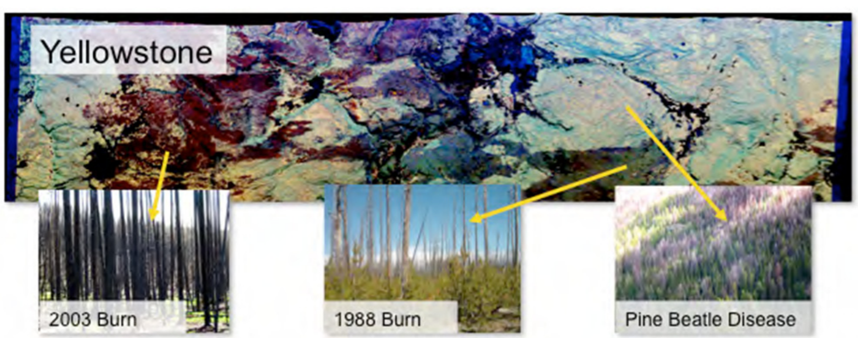
Proposed DESDynI Earth Radar Mission Overview

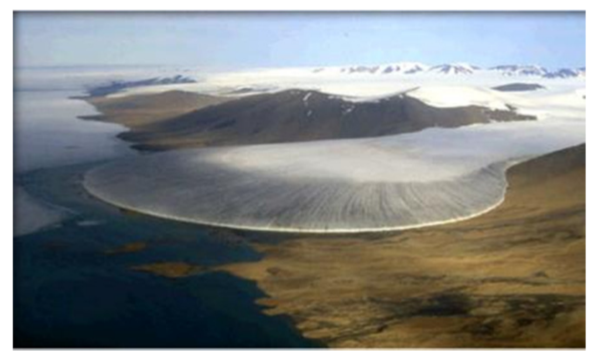
DESDynI: Deformation Ecosystem Structure Dynamics of Ice



Mission Objectives:

- Determine the likelihood of earthquakes, volcanic eruptions, and landslides.
- Predict the response of ice sheets to climate change and impact on sea level.
- Characterize the effects of changing climate and land use on species habitats and carbon budget.
- Understand the behavior of subsurface reservoirs.



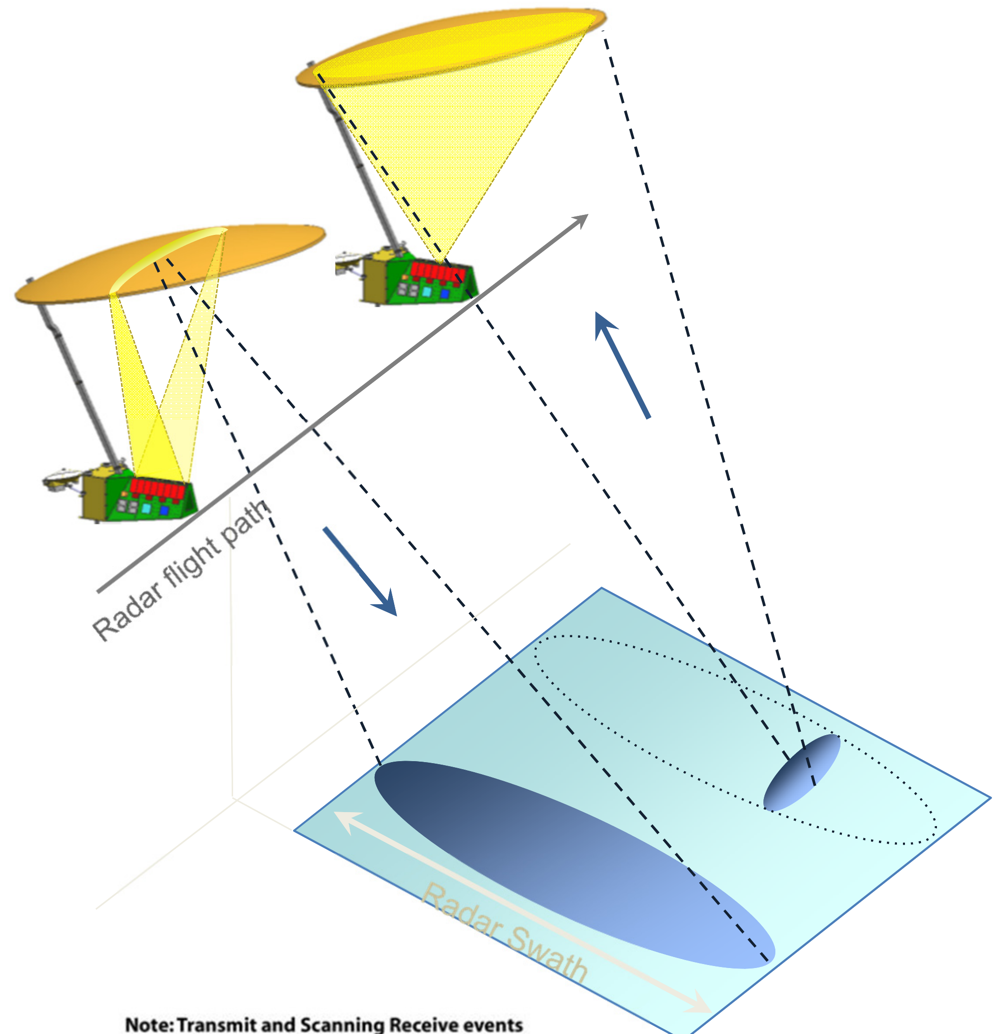


http://desdyni.jpl.nasa.gov/

SweepSAR Introduction

Advantages

- On Transmit, all Feed Array elements are illuminated *(maximum Transmit Power)*, creating the wide elevation beam
- On Receive, the Feed Array element echo signals are processed individually, taking advantage of the full Reflector area *(maximum Antenna Gain)*
- Uses digital beamforming to provide wide measurement swath
  - DBF allows multiple simultaneous echoes in the swath to be resolved by angle of arrival
- Uses large reflector to provide high aperture gain
  - Full-size azimuth aperture for both transmit and receive
  - Full-sized elevation aperture on receive
  - Aperture size effectively reduced on transmit to provide full-swath illumination
- Only need to store and process data from feed array elements being illuminated by an echoes
  - This can be predicted with *a priori* knowledge of measurement geometry (orbit, pulse timing and topography)

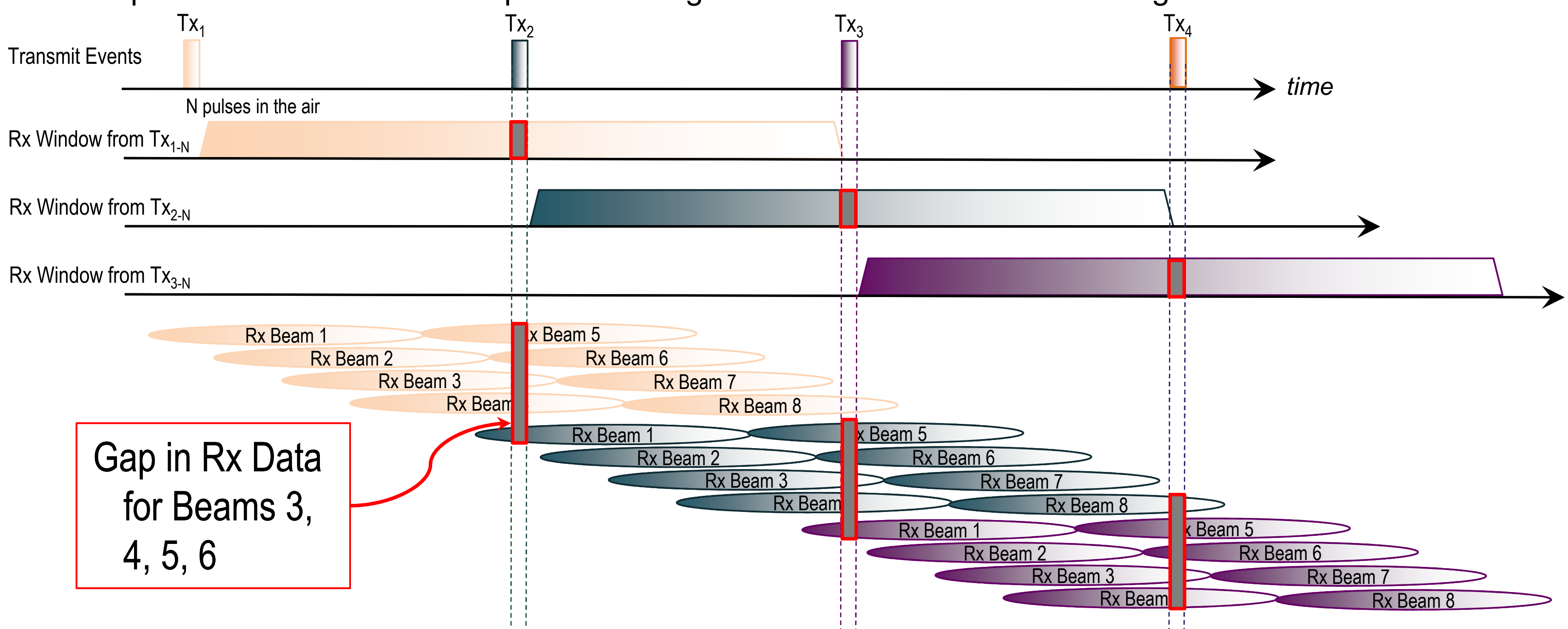


Note: Transmit and Scanning Receive events overlap in time and space. Along-track offset shown is for clarity of presentation only.

SweepSAR Pulse Timing

- Conventional Radar data acquisition timing – Receive Window is within the Inter-Pulse Period (IPP):

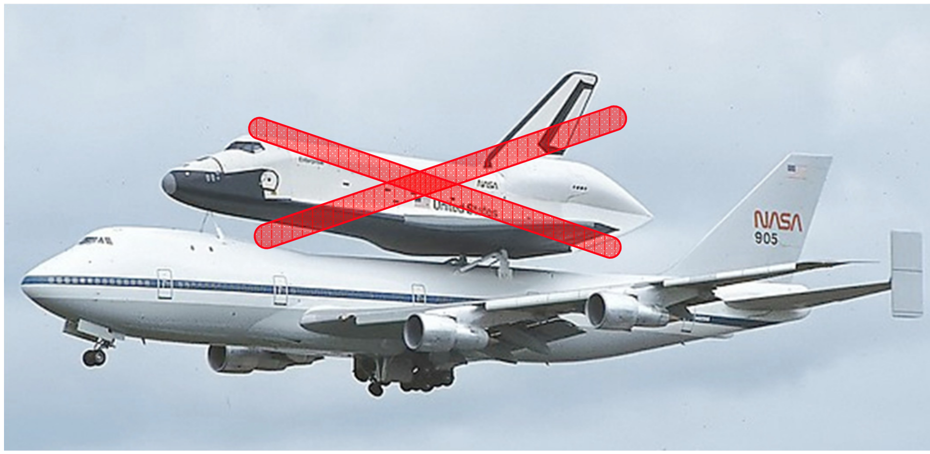
- SweepSAR wide-swath data acquisition timing – Receive Window extent is longer than an IPP:



- The Receive channels ("Rx Beams") that are active during a Transmit event are blanked for the duration of the Transmit pulse, resulting in gaps in the swath

SweepSAR Airborne Demo

- Now that the shuttle has finished flying…

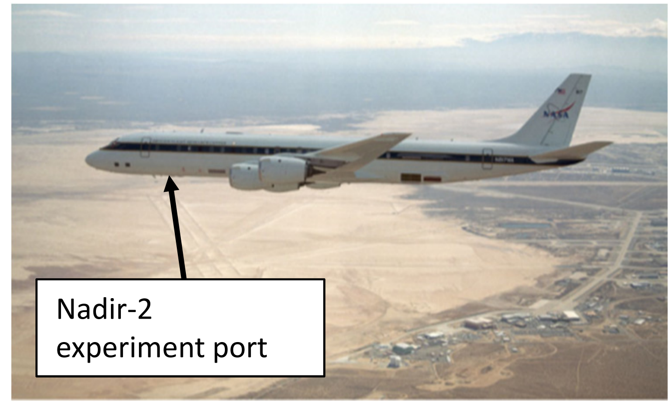


Surprisingly, this concept was rejected.

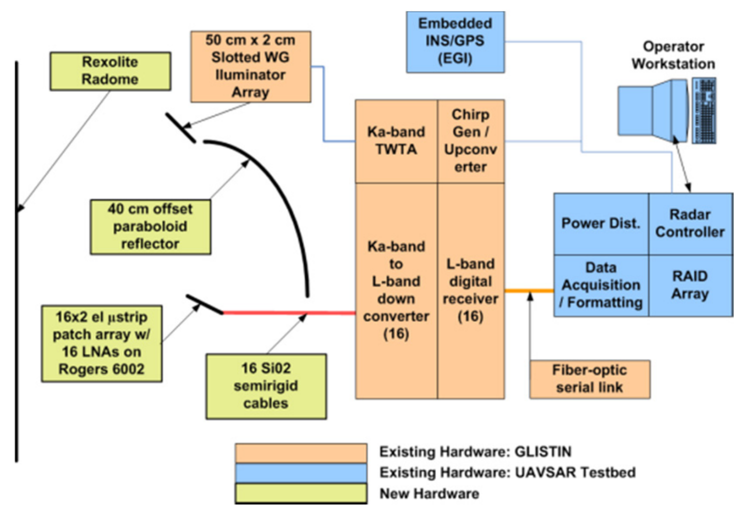
SweepSAR Airborne Demo Overview

- Ka-band (35.6 GHz) airborne SweepSAR using array-fed reflector and digital beamforming
  - 8 simultaneous receive beams generated by 40-cm offset-fed reflector an 8-element active array feed
  - 8 digital receiver channels, all raw data recorded
  - Receive antenna system is approximately 1/28th scale of proposed DESDynI SAR antenna
  - 16-channel capable, only 8 channels used during initial experiment
- Supports radar instrument development and risk mitigation for proposed DESDynI mission:
  - Demonstrates first-of-a-kind, real-world performance of SweepSAR with array-fed reflector
  - Reduces risk by shaking out engineering issues that are not predicted by simulation
  - Demonstrates performance of critical beamforming and calibration techniques
    - Identify, quantify and mitigate error sources
    - Trade algorithm performance vs. computational resource consumption

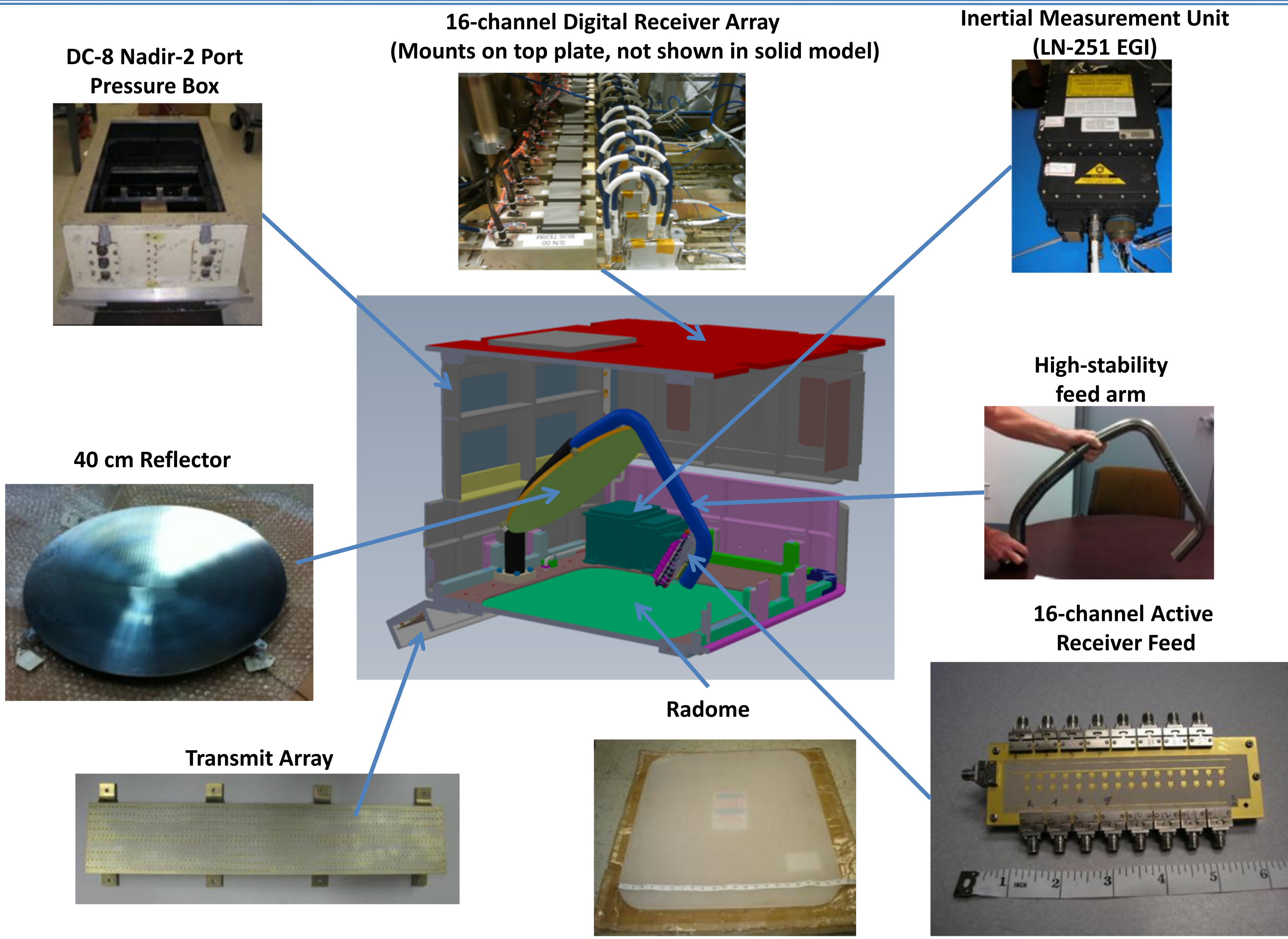
NASA DC-8



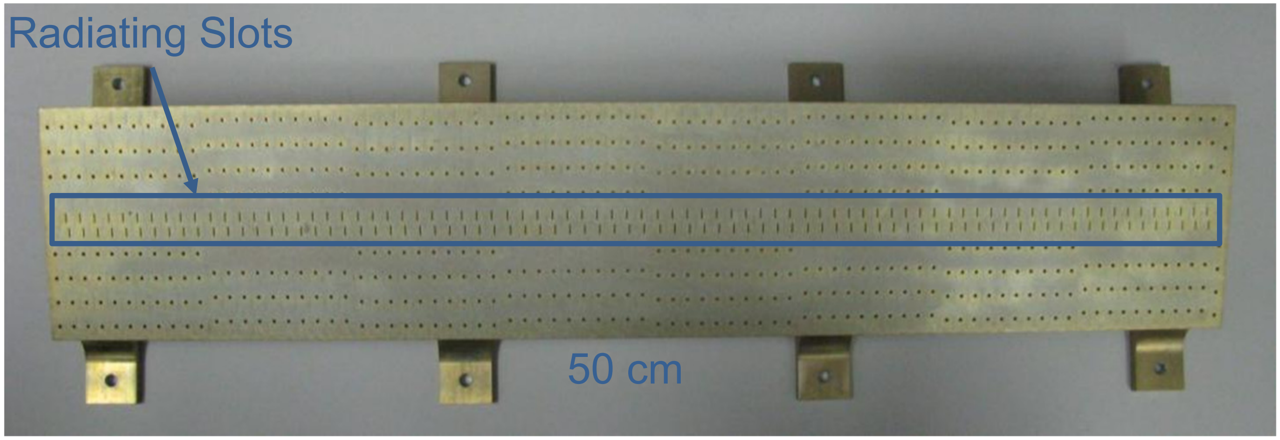
SweepSAR Demo Block Diagram



SweepSAR Airborne Demo Hardware



Transmit Antenna



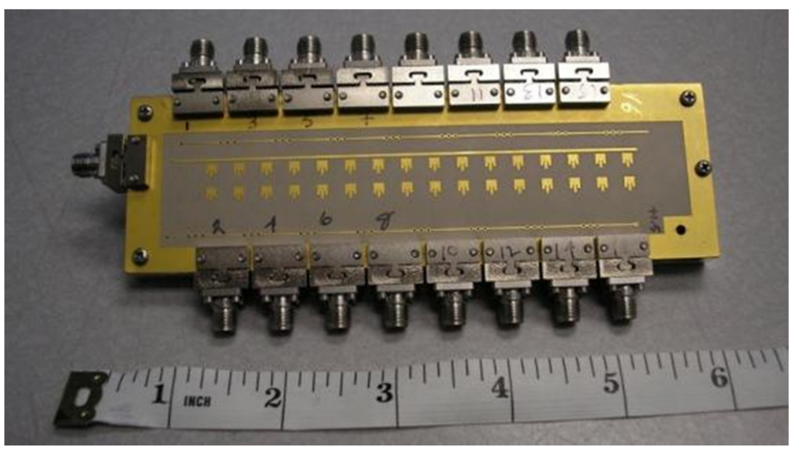
~2 cm
(active region)

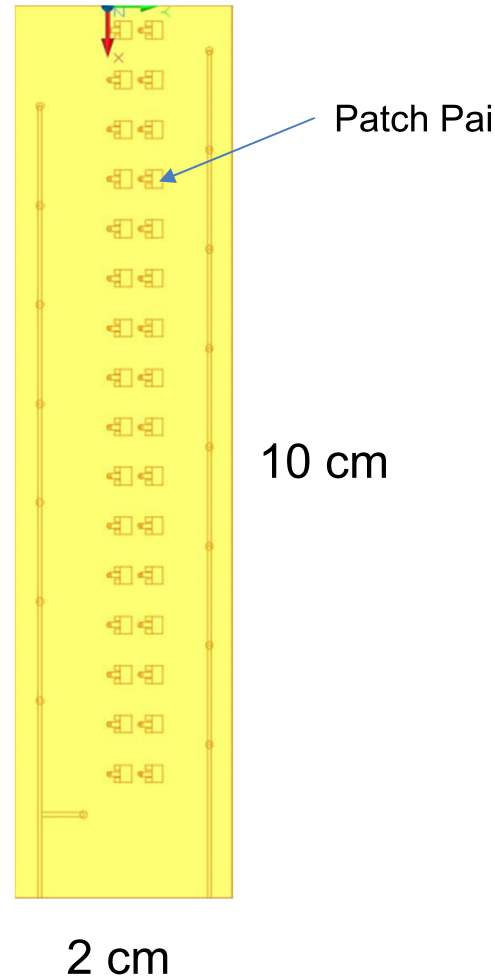
- Dip-brazed, slotted waveguide array (JPL design)
- Approximate dimensions: 50 cm (azimuth) x 2 cm (elevation)
- Beamwidth: 1 degree (azimuth) x 20 degrees (elevation)
- Successful design from GLISTIN Airborne Interferometer

Ka-band Receive Feed Array

- 32 microstrip patch radiators arranged in 16 pairs
- One low-noise amplifier (LNA) for every pair
- Low-loss temperature stable substrate
- Embedded calibration signal injection path
  - Calibration data collected continuous during flight
- 16 connectors on back connect to DBF array using phase stable coaxial cables

16-channel Active Receiver Feed



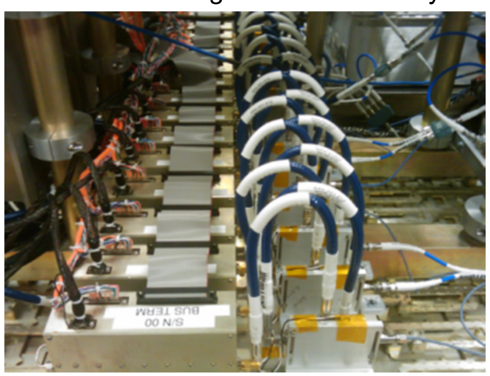


Digital Beamforming Architecture

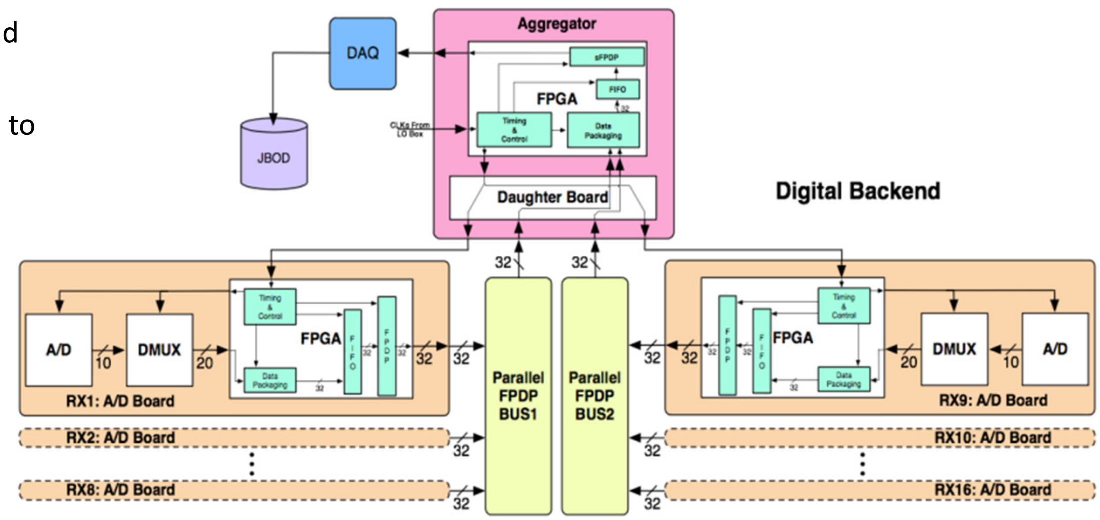
<u>Beamforming Data System</u>

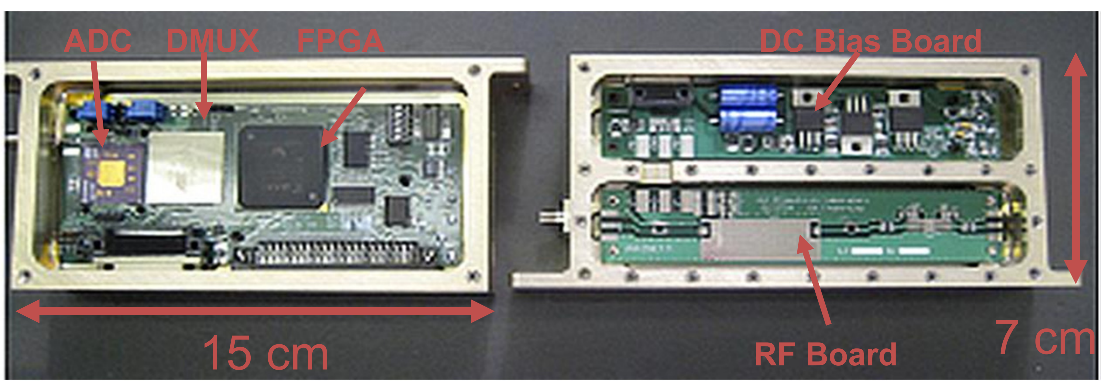
- 16 L-band Digital Receivers
  - 16 Ka-band signals are converted to L-band
- Two parallel FPDP data busses (8 receivers each)
- Aggregator board multiplexes all data streams on to as single serial FPDP connection
- All data is written to a high speed disk array (JBOD – "just a bunch of disks")

16-channel Digital Receiver Array



<u>DBF System Block Diagram</u>

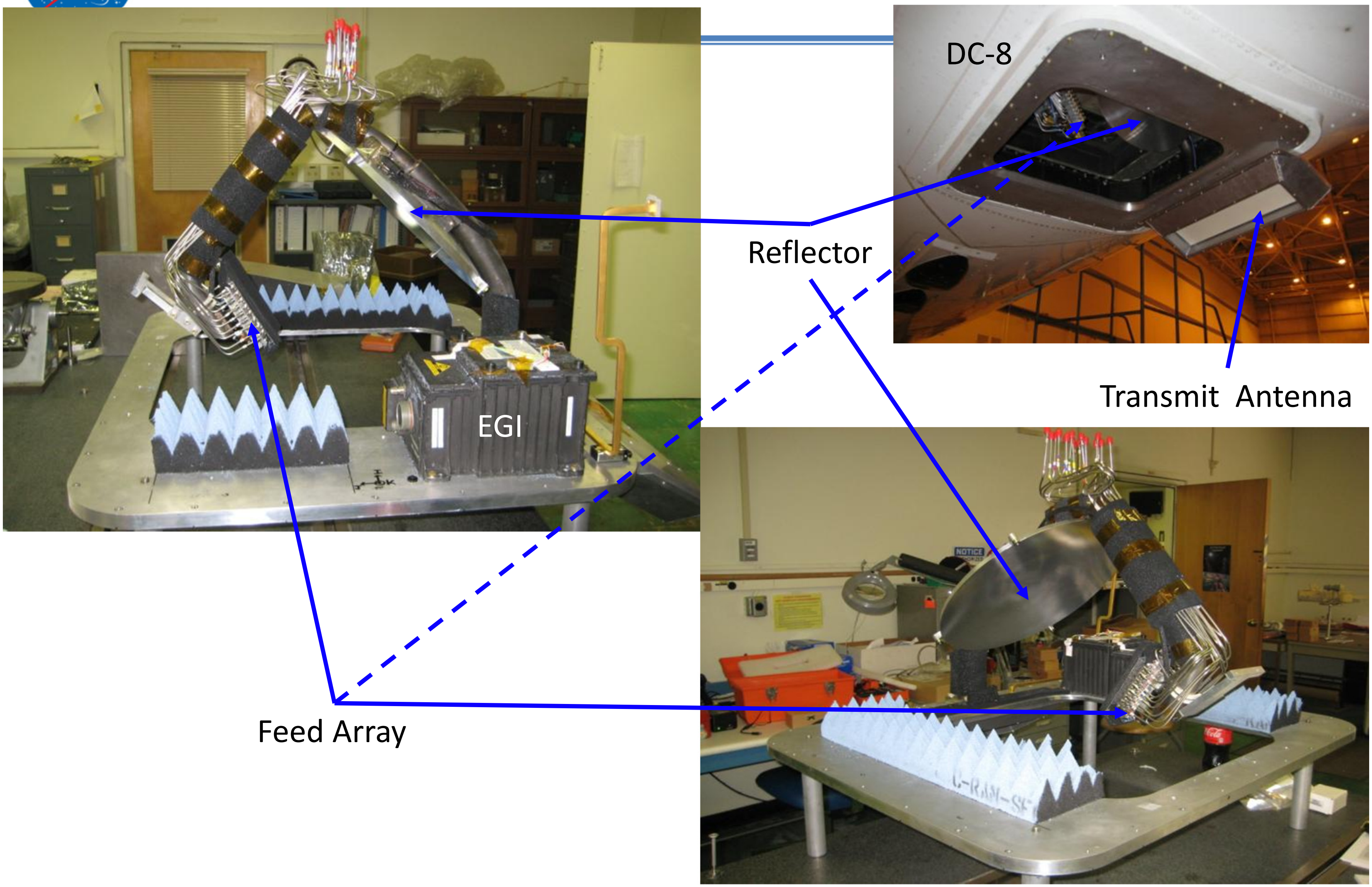




<u>L-band Digital Receiver</u>

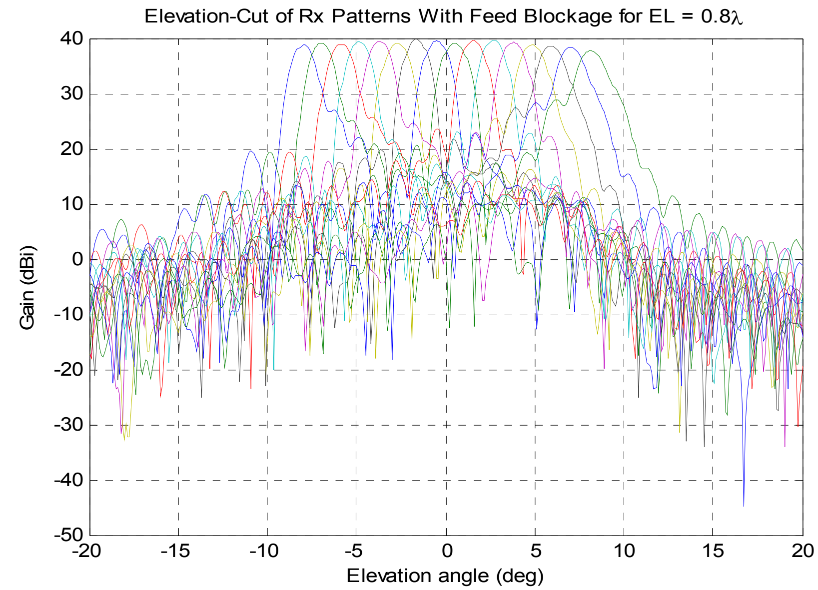
- Input 1215-1300 MHz
- Input analog bandwidth: 3.3 GHz
- Sample rate 240 Ms/s @ 10 bits resolution
- Digital demodulation and filtering using Xilinx Virtex 5 FPGA
- Output bandwidth: 80 MHz
- Data output over front-panel data port (FPDP)

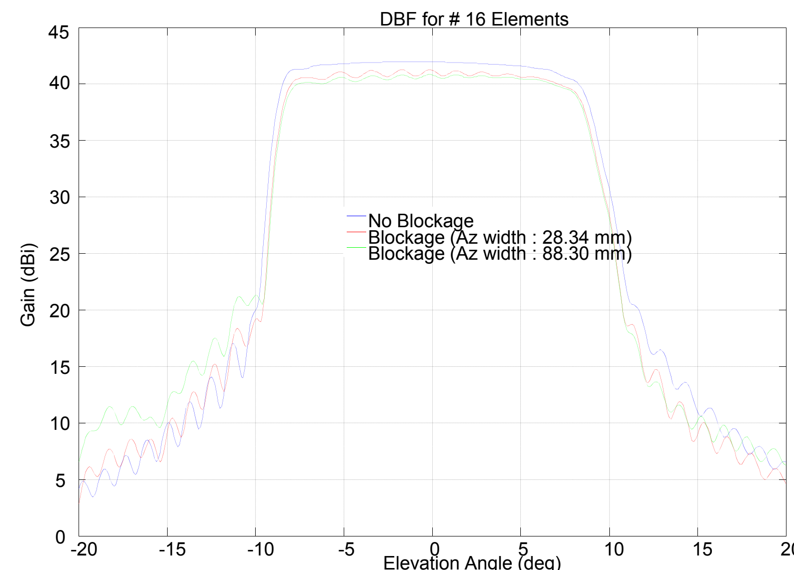
Hardware Photos



Predicted Beamforming Performance

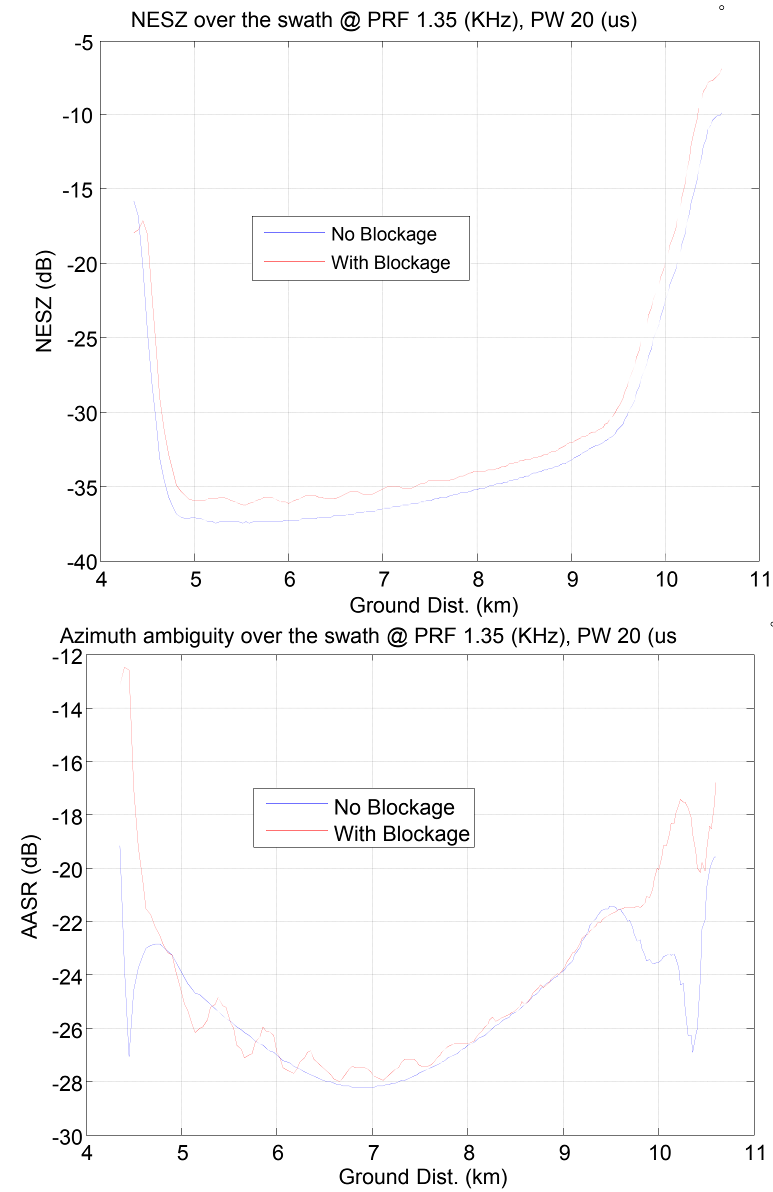
- Studied beamforming performance
  - HFSS used to generate feed patterns
  - Ticra GRASP used to model reflector/feed system
- Modeling included feed blockage and obstructions at edge of beam due to antenna mounting in aircraft
- Feed blockage causes small reduction in gain as well as gain ripples across the swath
- Similar to proposed DESDynI antenna models





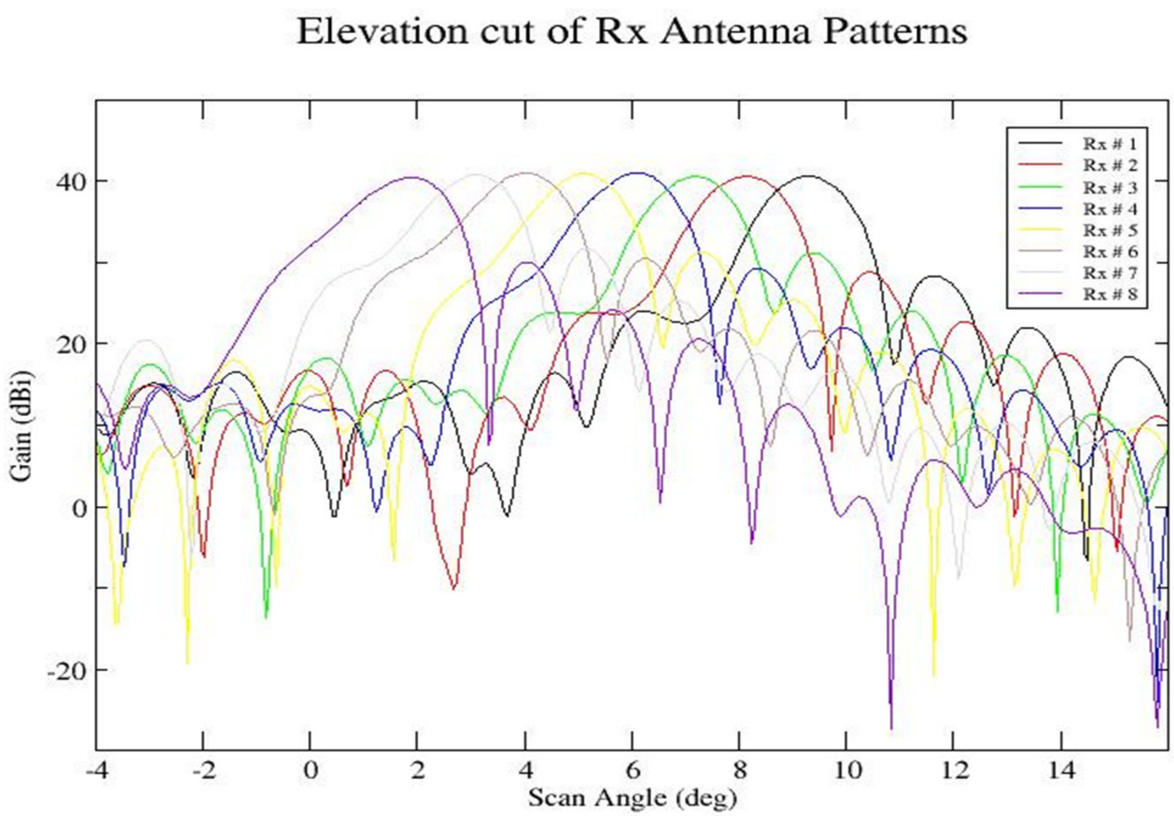
Predicted SNR and Azimuth Ambiguity Performance

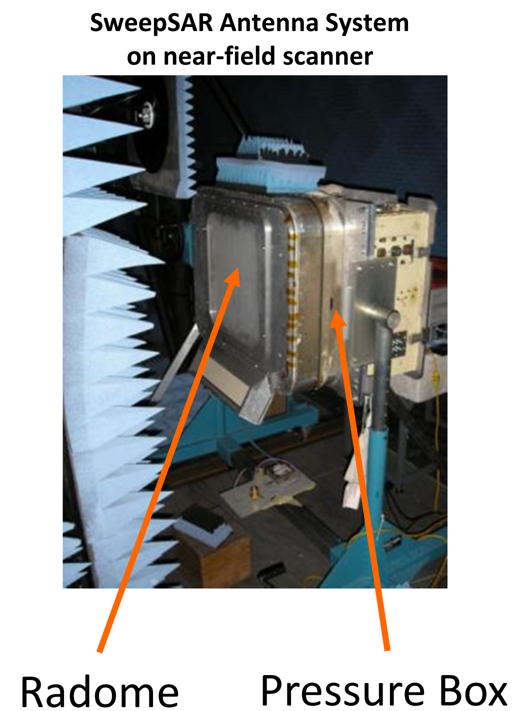
- Excellent sensitivity (-35 dB NESZ) using 20 us pulse
- Enough SNR margin to still have good sensitivity for short-pulse experiment modes (2us)
- Azimuth ambiguities < -20 dB (1350 Hz PRF)
- No significant range ambiguities using normal PRF
  - Can deliberately introduce range ambiguities and data collection gaps using staggered PRF scheme to place multiple pulses in swath



Measured Receive Antenna Patterns

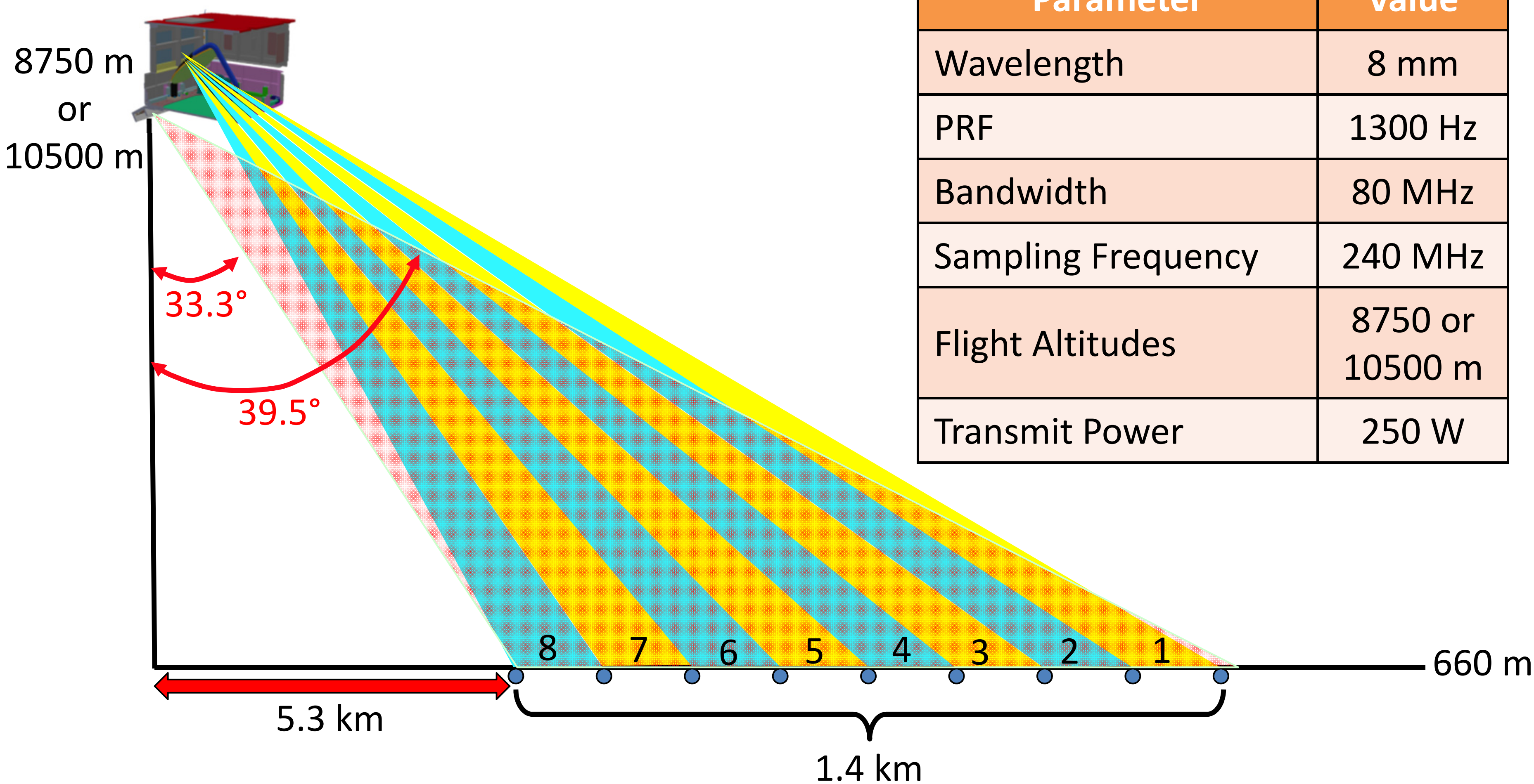
- Complex antenna patterns (amplitude and phase) measured for the 8 receive beams.
- Beamwidth is approximately 1° and the peak sidelobe level is around -10 dB.





Radar Parameters and Mapping Geometry

- The eight beams map a swath extending from 33.3°-39.5° that gives a swath width of 1.4 km.



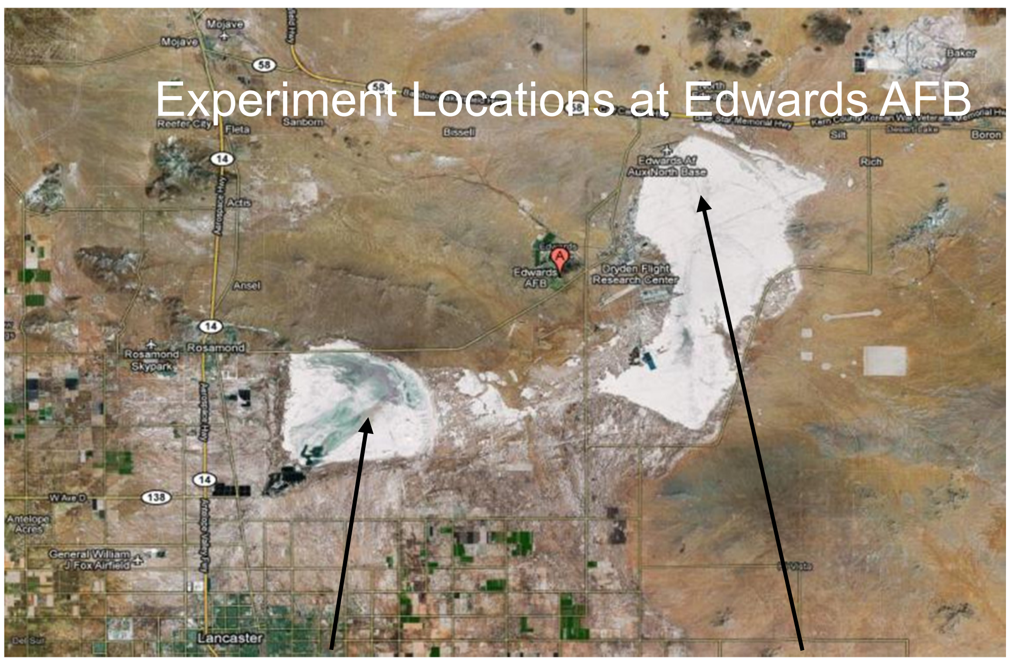
Radar Parameters

Parameter	Value
Wavelength	8 mm
PRF	1300 Hz
Bandwidth	80 MHz
Sampling Frequency	240 MHz
Flight Altitudes	8750 or 10500 m
Transmit Power	250 W

Not drawn to scale

SweepSAR Test Site

- Data Collection Flights
  - Data collected using corner reflectors deployed in radar dark areas at Edwards AFB
  - Two sites identified:
    - Rosamond Lake – UAVSAR calibration array with large 2.4 m reflectors
    - Rogers Lake – Smaller 1 m reflectors deployed
    - Reflector spacing designed to effectively measure beamformed pattern performance

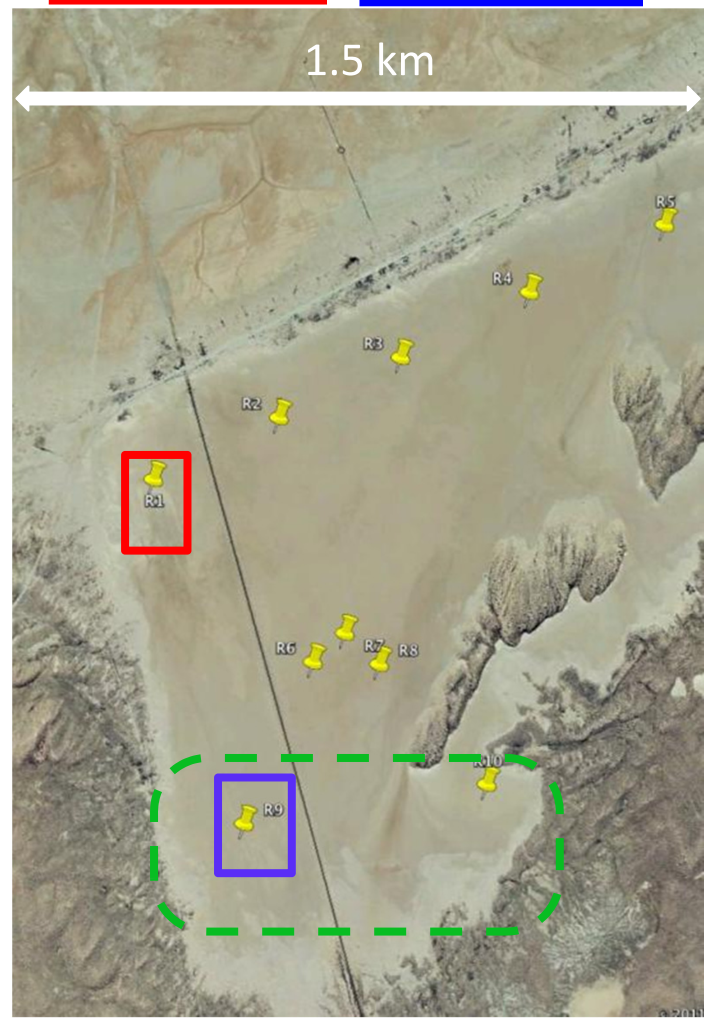


Rosamond Lake **Rogers Lake**

R1

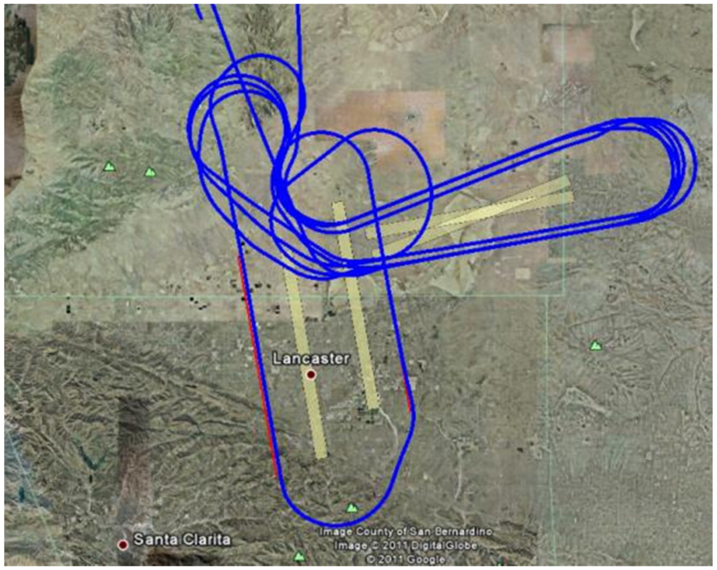
R9

Flight Direction 80° Heading



SweepSAR Demo Successful Test Flights

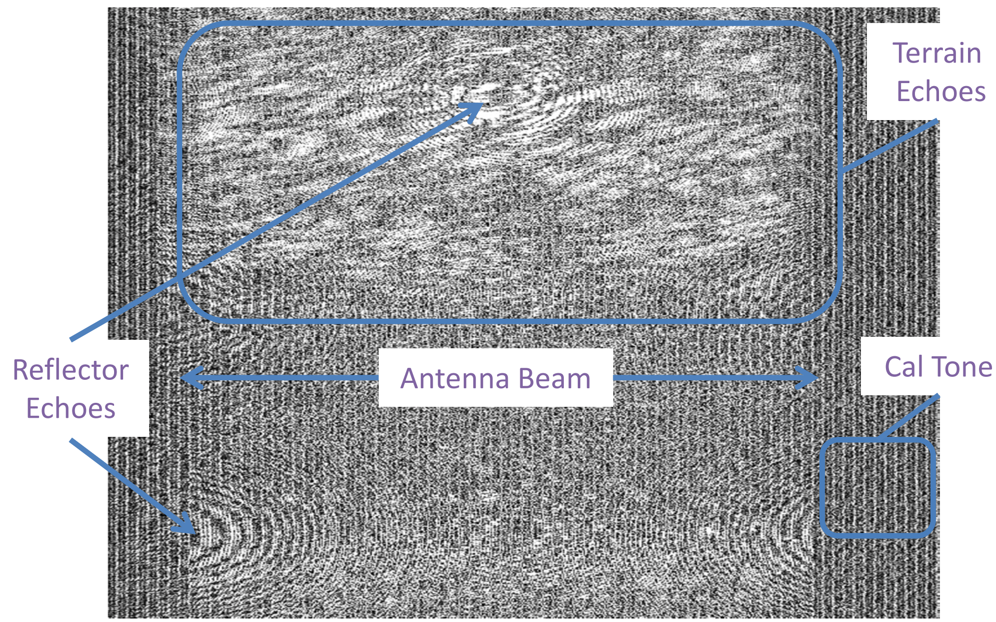
Flight Track and Swaths for Flight #2



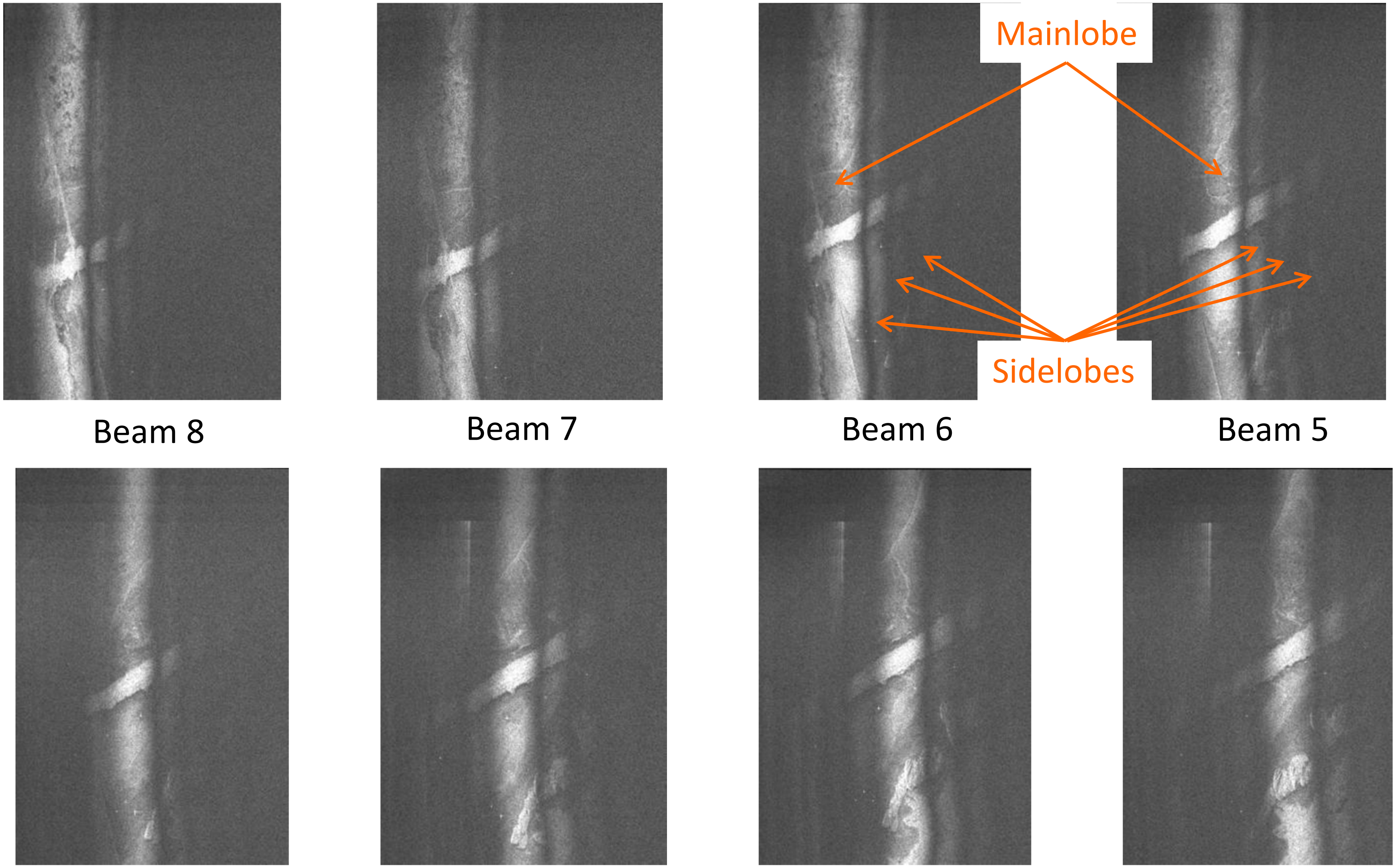
SweepSAR Demo Flight Team

- SweepSAR Flight History
  - Two flights flown on July 7 and July 9, 2011
  - 3.5 hours per flight
  - 12 data collection lines
  - >200 GB collect during Flight #2
- Flight 1 used a PRF of 100 Hz so was not critically sampled in azimuth – but showed we had a functioning radar!
- Data quality for Flight @2 is good except for gain anomaly on receiver #4

Raw Radar Data (Rogers Lake, Beam #5)



Individual Beam Imagery

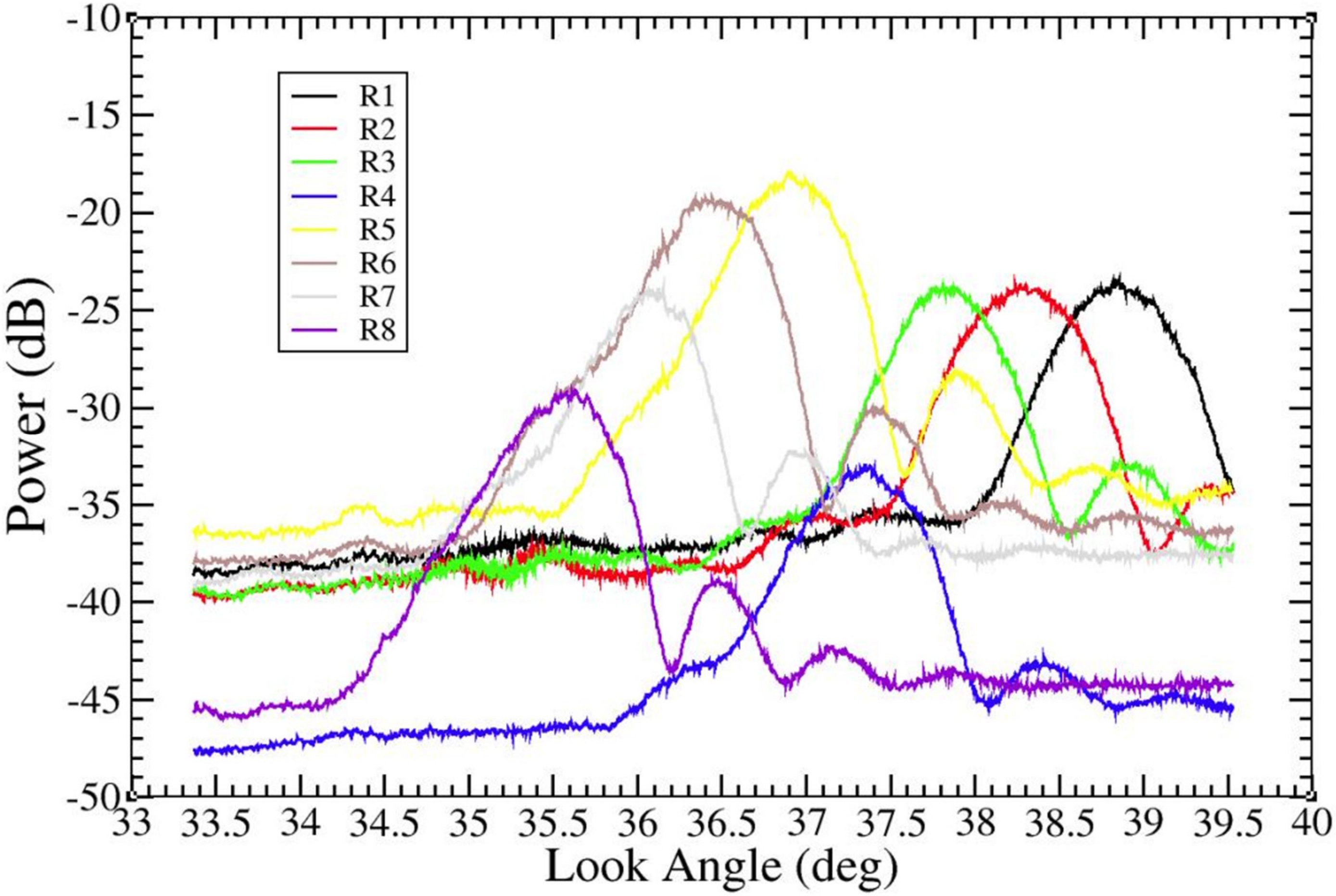


Beam 8 Beam 7 Beam 6 Beam 5

Beam 4 Beam 3 Beam 2 Beam 1

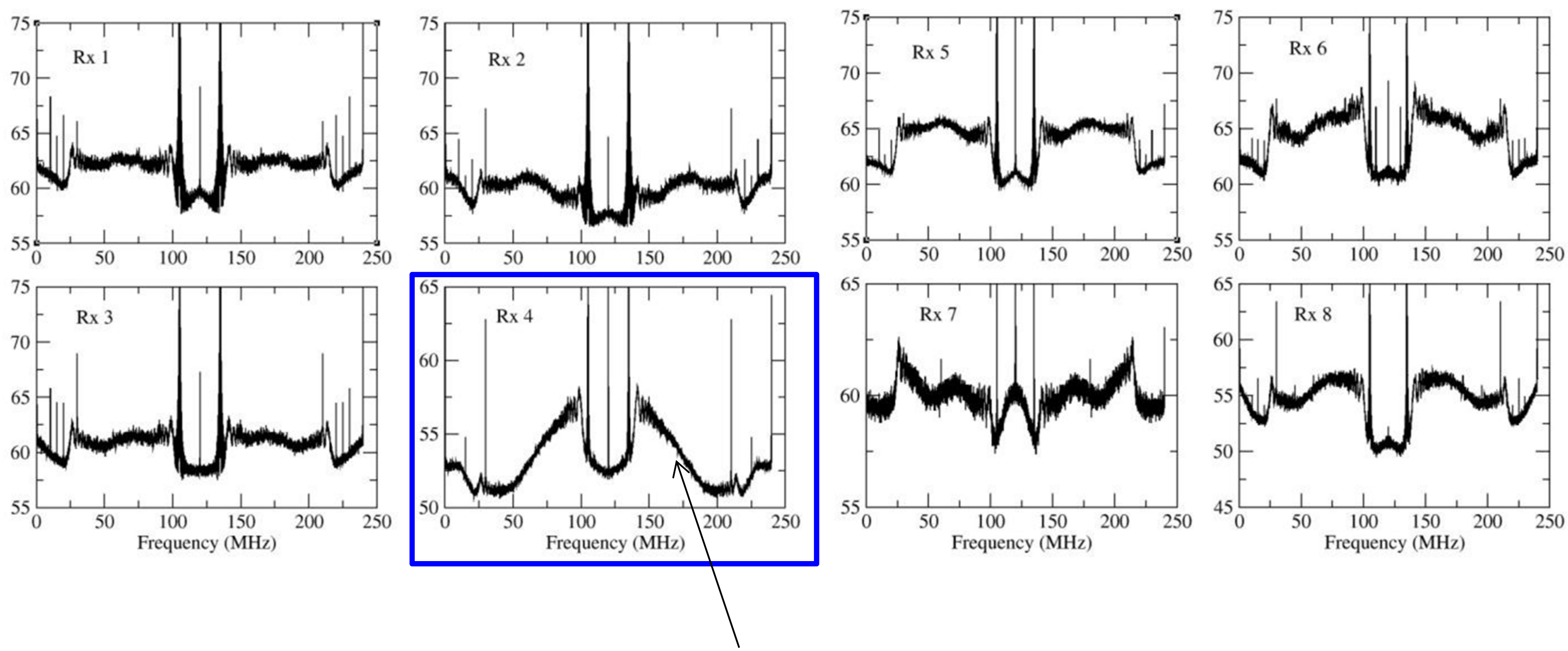
Power Profiles

- Power profiles are in reasonable agreement with measured antenna patterns.
- Note power in channel 4 and 8 are low as expected from the spectral plots.



Channel Spectra

- Range spectra were generated for the 8 receive channels.
  - Power on channel 8 is low relative to the other channels by 3-5 dB.
  - Channel 4 is lower in power and shows a distorted spectrum.
  - Still able to form imagery on Channel 4, however it presents a problem to beam forming.



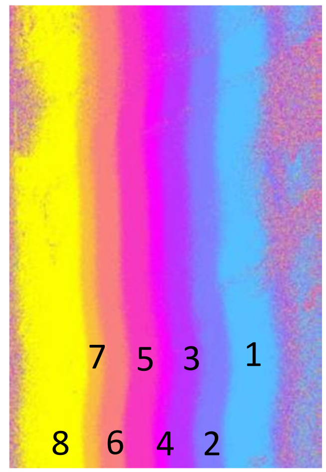
Distorted Spectra

Corner Reflector Image

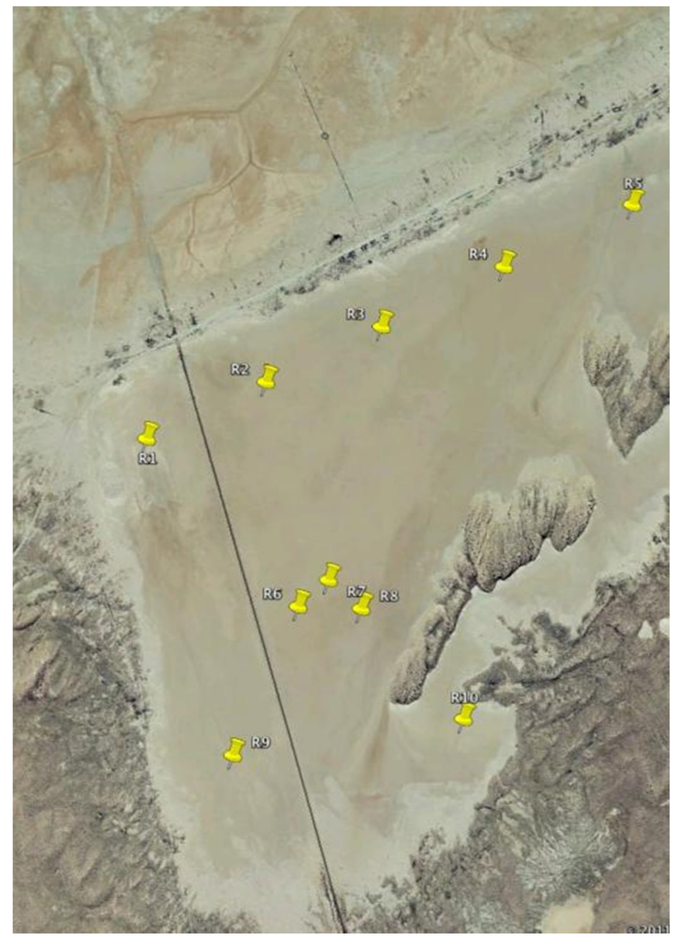
- Simple maximum power combining algorithm used to generate a simple mosaic of the individual beam images.

Beam Mosaic Image

Beam Number Image

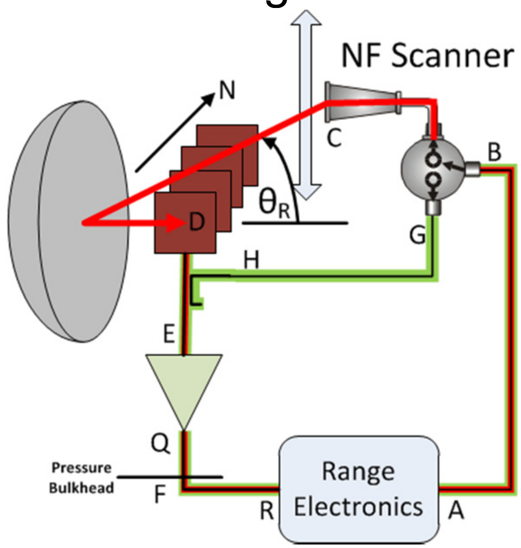


Google Earth Image



SweepSAR Demo Receive Array Calibration

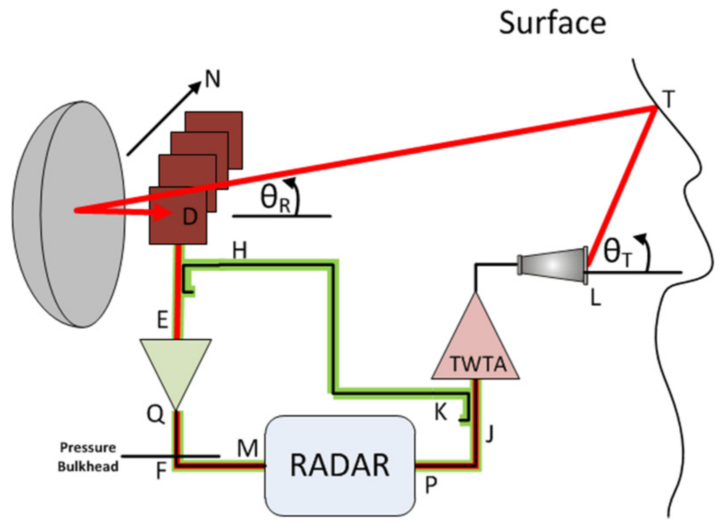
Antenna Range Calibration



Pattern Measurement: $S_{AB}\, S_{BC}\, P_R(N,\theta_R) S_{DE}(N) S_{EQ}(N) S_{QF}(N) S_{FR}$

NF Range Calibration: $S_{AB}\, S_{BH}\, S_{HE}(N)\, S_{EQ}(N)\, S_{QF}(N)$

SweepSAR Demo Operation



Radar: $S_{PJ}\, S_{JL}\, P_T(\theta_T)\, S_{LT}(\theta_T)\, \sigma\, S_{TD}(N)\, P_R(N,\theta_R)\, S_{DE}(N)\, S_{EQ}(N)\, S_{QF}(N)\, S_{FM}(N)$

Airborne Calibration: $S_{PJ}\, S_{JH}\, S_{HE}(N)\, S_{EQ}(N)\, S_{QF}(N)\, S_{FM}(N)$

- S_{XY} is complex transmission from point x to point (either through components or free space)
- $S_{XY}(N)$ varies by element number
- $P(N,\theta)$ is far-field antenna pattern (varies by element number and angle of arrival)
- σ is the complex reflection from target T

Remove factors independent of N:

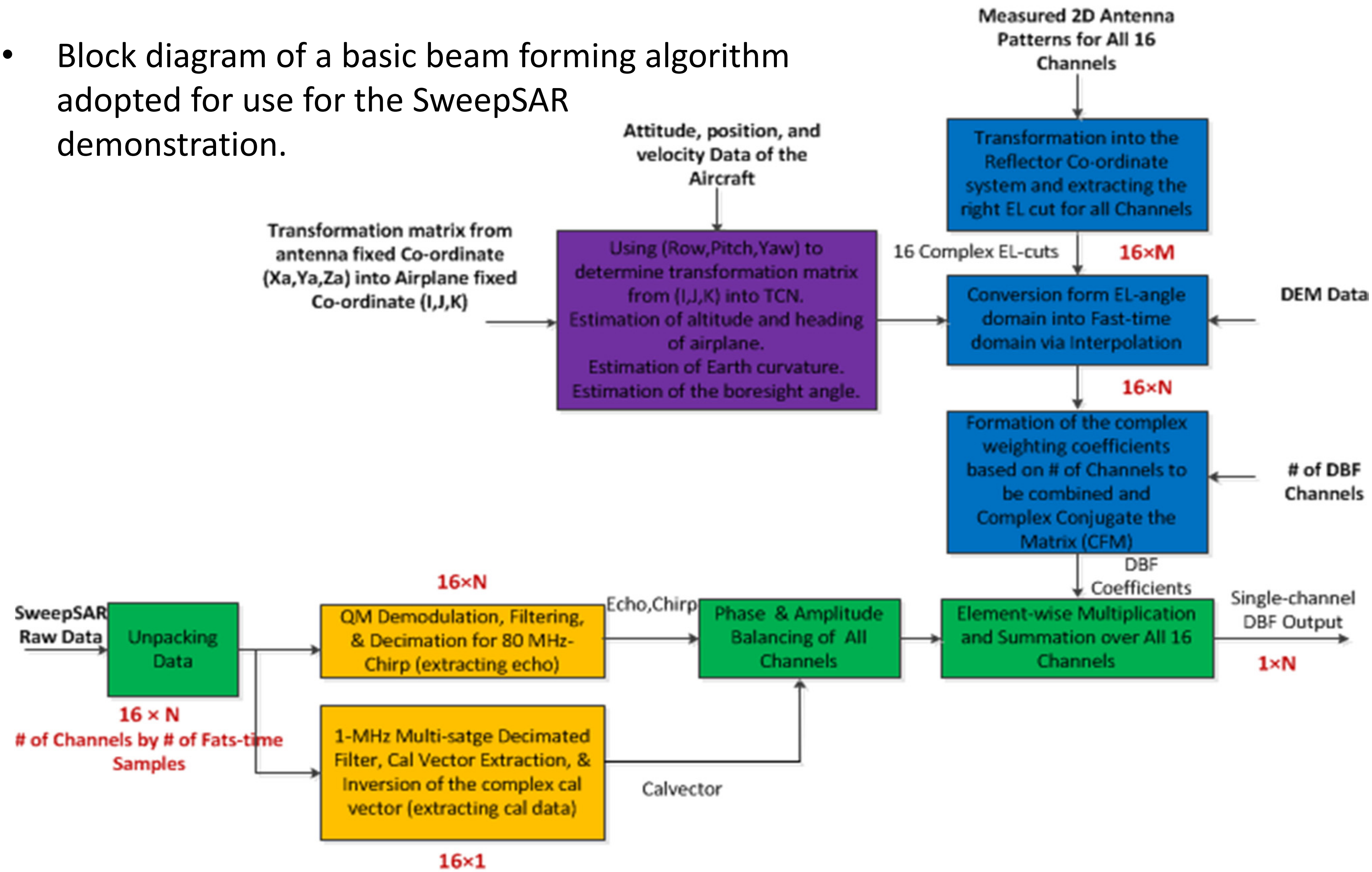
- NFPat: $P_R(N,\theta_R)\, S_{DE}(N)\, S_{EQ}(N)\, S_{QF}(N)$
- NFCal: $S_{HE}(N)\, S_{EQ}(N)\, S_{QF}(N)$

- Radar: $S_{TD}(N)\, \underbrace{\overbrace{P_R(N,\theta_R)\, S_{DE}(N)\, S_{EQ}(N)\, S_{QF}(N)}^{\text{NFPat}}\, S_{FM}(N)}_{P'_R(N,\theta_R)}$
- AirCal: $S_{HE}(N)\, S_{EQ}(N)\, S_{QF}(N)\, S_{FM}(N)$

- AirCal / NFCal = $S_{FM}(N)$
- $P'_R(N,\theta_R)$ = (NFPat/NFCal)(AirCal)
- $P'_R(N,\theta_R)$ is effective element pattern used for DBF

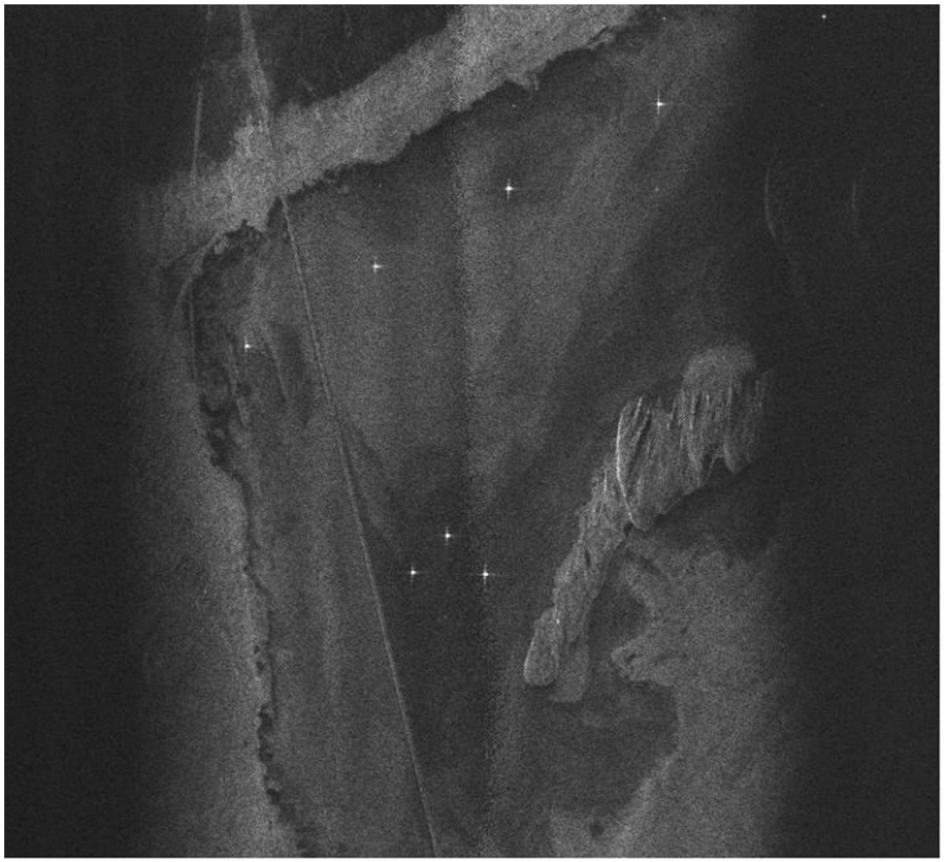
SweepSAR Digital Beam Forming Algorithm

- Block diagram of a basic beam forming algorithm adopted for use for the SweepSAR demonstration.

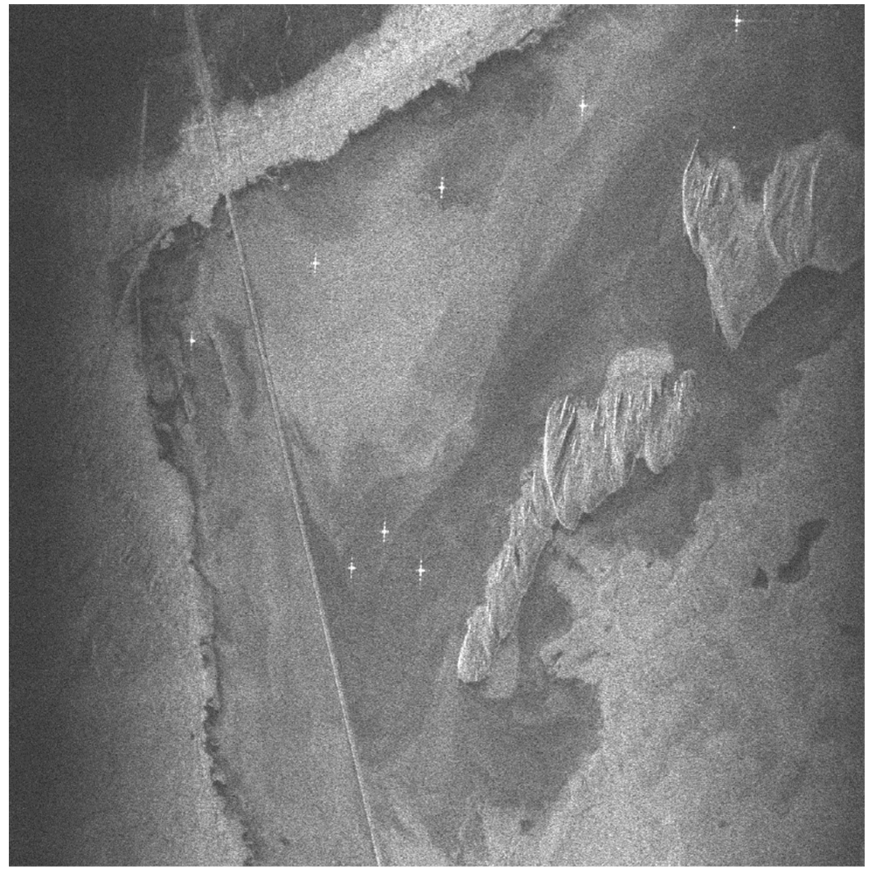


Rogers Lake Beam Formed Imagery

- Pass 11 imagery before and after beam forming.



Simple Mosaic

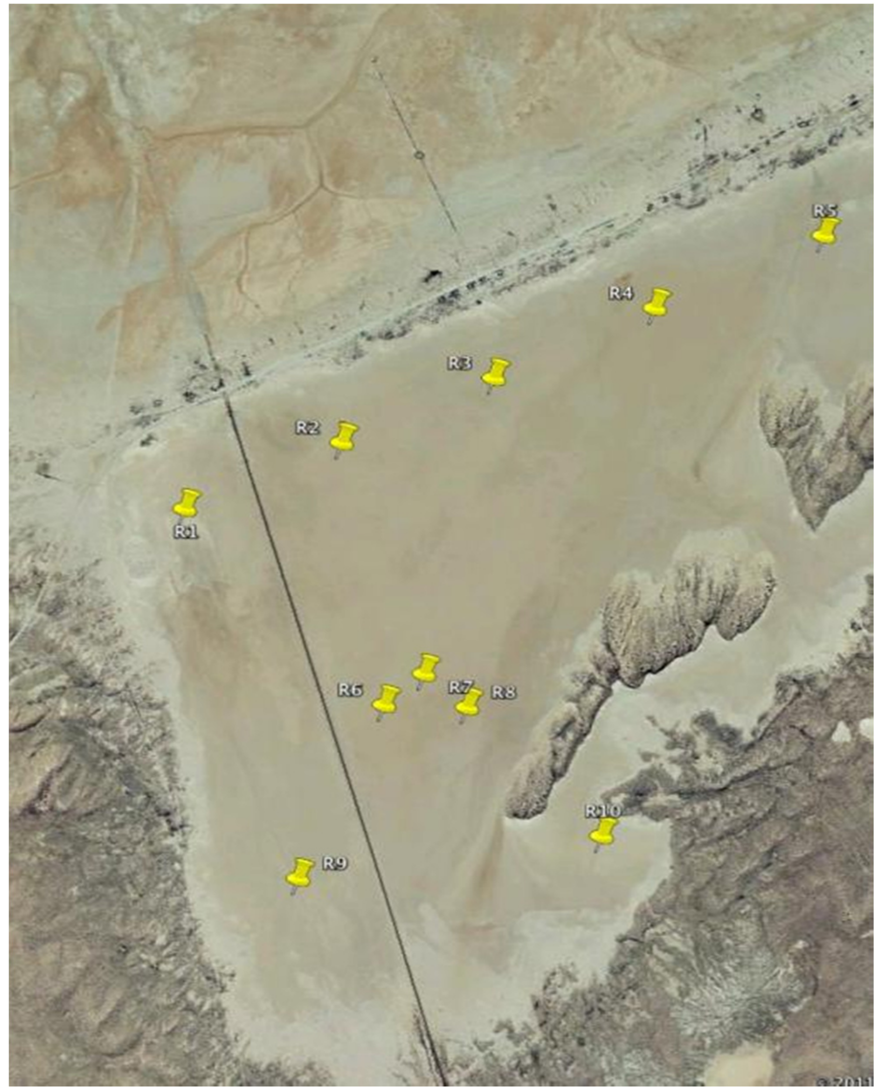


Beamformed Image

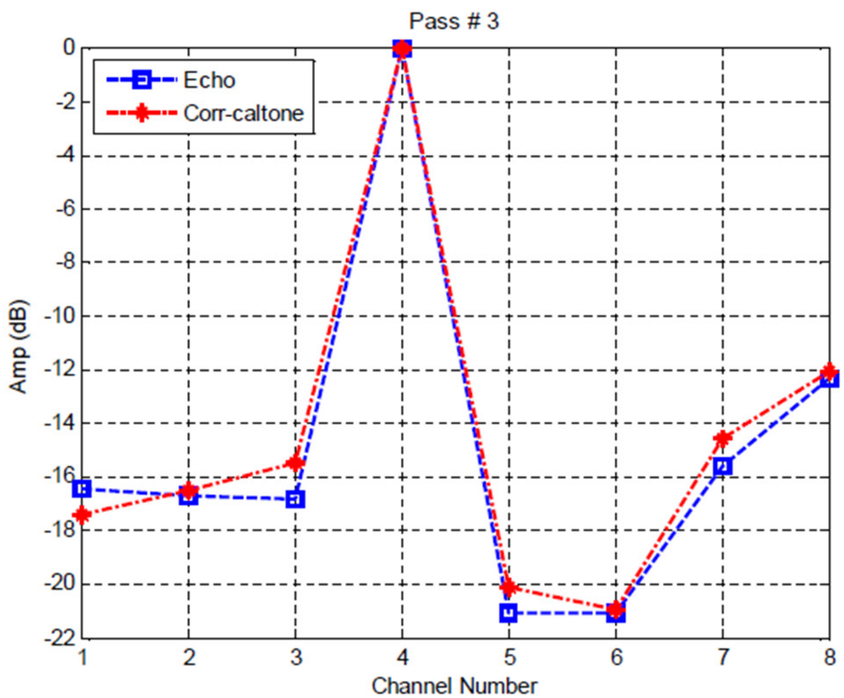
Corner Reflectors Images

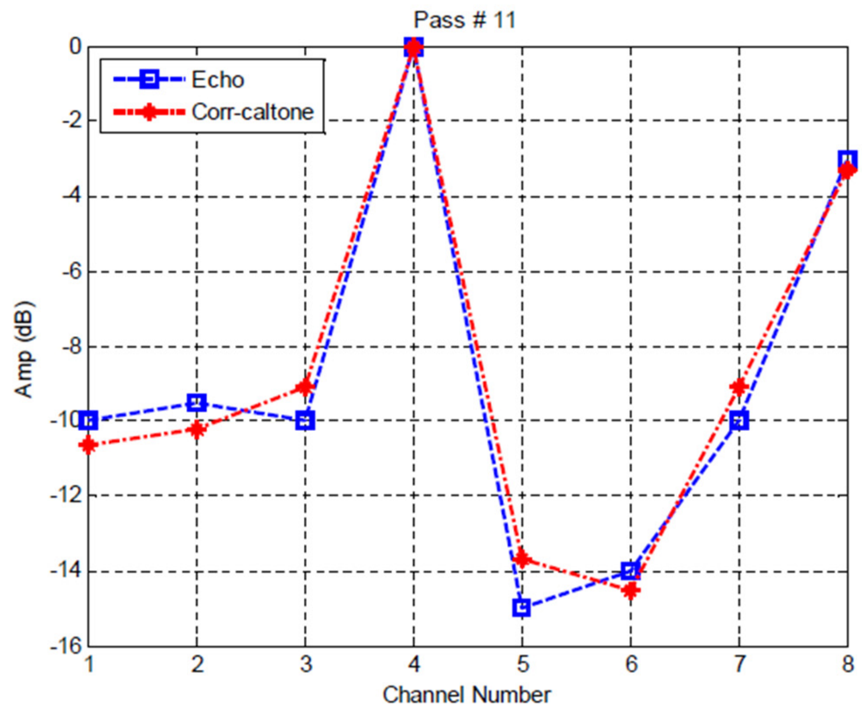
Beamformed Image

Google Earth



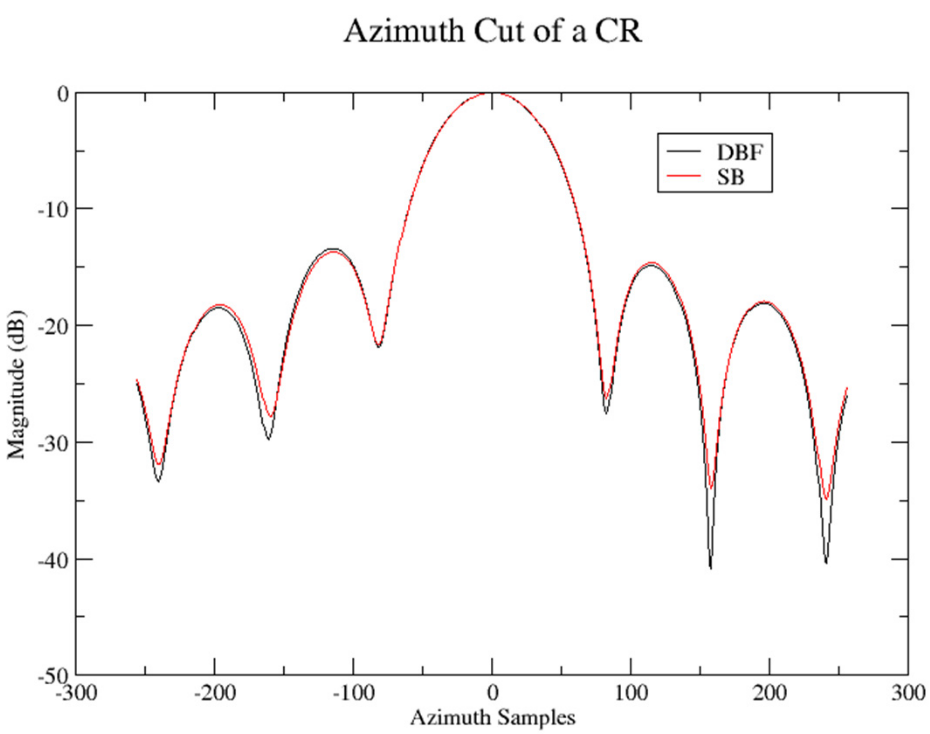
Calibration Values vs. Echo Power

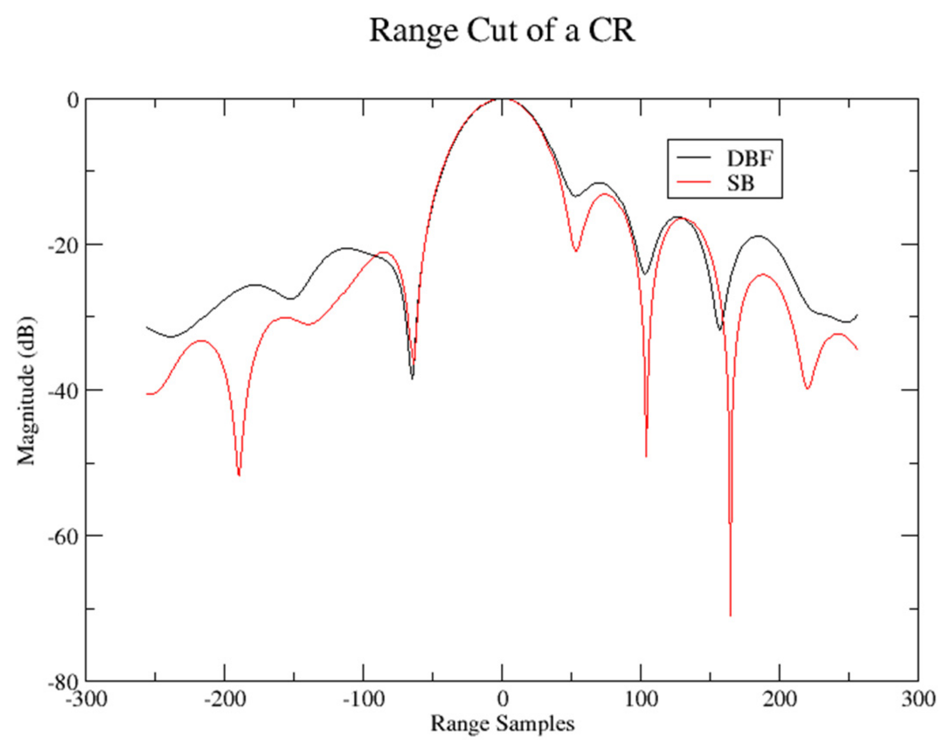




- Pass #3 and #11 are same uniform lake bed scene
- Measured calibration signal tracks w/ echo power
- Functions even with low SNR, unstable receiver (#4)

Point-Target Responses





- As expected, no degradation in azimuth response
- Minor degradation of range sidelobes due to digital beamforming errors

Palmdale, CA Beamformed Imagery

Beamformed Ka-band SweepSAR Image

Visible image (Google Earth)

Conclusions

- NASA/JPL has developed SweepSAR technique that breaks typical SAR trade space using time-dependent multi-beam DBF on receive
- Developing SweepSAR implementation using array-fed reflector for proposed DESDynI Earth Radar Mission concept
- Performed first-of-a-kind airborne demonstration of the SweepSAR concept at Ka-band (35.6 GHz).
- Validated calibration and antenna pattern data sufficient for beam forming in elevation.
  - Provides validation evidence that the proposed DESDynI SAR architecture is sound.
  - Functions well even with large variations in receiver gain / phase
- Future plans include using prototype DESDynI SAR digital flight hardware to do the beam forming in real-time onboard the aircraft.

Acknowledgements

- The JPL SweepSAR Airborne Demonstration Team:
  - Roger Chao, Ernie Chuang, Hirad Ghaemi, Brandon Heavey, Scott Hensley, Eric Liao, Sean Lin, Timothy Miller, Dragana Perkovic, Momin Quddus, Jan Martin, Thierry Michel, Mauricio Sanchez- Barbetty, Scott Shaffer, Joanne Shimada, Jordan Tanabe, Tushar Thrivikraman
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Thank you for your attention!